

Fate of ^{15}N -labelled fertilizer applied to spring barley grown on soils of contrasting nutrient status

M.J. Glendining, P.R. Poulton, D.S. Powlson & D.S. Jenkinson
Soil Science Department, IACR-Rothamsted, Harpenden, Herts, AL5 2JQ, UK *

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Abstract

An experiment with ^{15}N -labelled fertilizer was superimposed on the Rothamsted Hoosfield Spring Barley Experiment, started in 1852. Labelled $^{15}\text{NH}_4$ $^{15}\text{NO}_3$ was applied in spring at (nominal) rates of 0, 48, 96 and 144 kg N ha^{-1} . The labelled fertilizer was applied to microplots located within four treatments of the original experiment: that receiving farmyard manure (FYM) annually, that receiving inorganic nutrients (PK) annually and to two that were deficient in nutrients: applications were made in two successive years, but to different areas within these original treatments. Maximum yields in 1986 (7.1 t grain ha^{-1}) were a little greater than in 1987. In 1987, microplots on the FYM and PK treatments gave similar yields, provided enough fertilizer N was applied, but in 1986 yields on the PK treatment were always less than those on the FYM treatment, no matter how much fertilizer N was applied. In plots with adequate crop nutrients, about 51% of the labelled N was present in above-ground crop and weed at harvest, about 30% remained in the top 70 cm of soil (mostly in the 0–23 cm layer) and about 19% was unaccounted for, all irrespective of the rate of N application and of the quantity of inorganic N in the soil at the time of application. Less than 4% of the added fertilizer N was present in inorganic form in the soil at harvest, confirming results from comparable experiments with autumn-sown cereals in south-east England. Thus, in this experiment there is no evidence that a spring-sown cereal is more likely to leave unused fertilizer in the soil than an autumn-sown one. With trace applications (ca. 2 kg N ha^{-1}) more labelled N was retained in the soil and less was in the above-ground crop. Where P and K were deficient, yields were depressed, a smaller proportion of the labelled fertilizer N was present in the above-ground crop at harvest and more remained in the soil.

Although the percentage uptake of labelled N was similar across the range of fertilizer N applications, the uptake of total N fell off at the higher N rates, particularly on the FYM treatment. This was reflected in the appearance of a negative Added Nitrogen Interaction (ANI) at the highest rate of application. Fertilizer N blocked the uptake of soil N, particularly from below 23 cm, once the capacity of the crop to take up N was exceeded. Denitrification and leaching were almost certainly insufficient to account for the 19% loss of spring-added N across the whole range of N applications and other loss processes must also have contributed.

Introduction

Spring barley (*Hordeum vulgare* L.) is widely grown in the European Union, producing 10% of the total cereal yield in 1993 (Eurostat, 1994). It is the most important spring-sown cereal in the UK, with 512,000 ha grown in 1993, 17% of the total UK cereal area (Nix, 1995). Much is known about the fate of fertilizer N applied in

spring to autumn-sown cereals in temperate climates (e.g. Macdonald et al., 1989, 1997; Powlson et al., 1986a,b; Recous et al., 1988). Spring-sown cereals have received somewhat less interest, even though they are generally considered to be less efficient at using fertilizer N than autumn-sown cereals, as they have a less developed root system when fertilizer N is applied in the spring, and are therefore more likely to leak N (Smith et al., 1984). Thus there may be a greater risk

* FAX No: + 441582760981.
E-mail Margaret.Glendining@bbsrc.ac.uk

of losses of N via leaching and gaseous emissions to the wider environment.

The aim of the work reported in this paper was to measure the recovery of ^{15}N -labelled fertilizer, applied to spring barley on soils of contrasting fertility. These contrasts were obtained by siting the ^{15}N experiment on one the "Classical" Experiments at Rothamsted, in which different long-term fertilizer and manure treatments have resulted in very different levels of organic matter and available nutrients. This paper is about the fate of the ^{15}N -labelled fertilizer in the year of application; the fate of the ^{15}N remaining in the soil at harvest over the following two years will be the subject of a further paper.

Materials and methods

The experimental site and fertilizer treatments

The experiment with ^{15}N -labelled fertilizer was sited on the Hoosfield Spring Barley Experiment at Rothamsted Experimental Station, Harpenden, SE England ($51^\circ 48' \text{ N}$, $0^\circ 21' \text{ W}$; altitude 128m). The soil (Batcombe series; classified as Aquic Paleudalf (USDA) or Chromic Luvisol (FAO)) is a flinty silty clay loam overlying Clay-with-flints (Avery and Catt, 1995). The topsoil, 0–23 cm, contains 20–25% clay ($< 2 \mu\text{m}$) and 50–55% silt (2–50 μm).

The Hoosfield Experiment was started in 1852 to test the effects of organic manure and inorganic fertilizers on the growth of spring barley (Lawes and Gilbert, 1873). Spring barley has been grown every year, except 1912, 1933, 1943 and 1967, when the experiment was bare fallowed to control weeds. Four treatments from the old experiment were selected for the work reported here: one receiving P and K fertilizer annually (the PK treatment), one receiving farmyard manure annually (FYM), one that received FYM between 1852 and 1871 (FYM-residue) and an unfertilized control (Nil). These long-term treatments have led to considerable differences in soil fertility and organic matter content (Table 1). For example, soil total N contents (0–23 cm) range from 0.100% N in the PK treatment, to 0.298% N in the FYM treatment. The FYM-residue treatment still contains 30% more total N than the PK and Nil treatments, even though FYM was last applied 115 years ago. Both the FYM-residue and the Nil treatments are now deficient in P and, to a lesser extent, in K.

The long-term treatments are applied to large unreplicated plots, which are separated by cropped discards (Figure 1).

Since 1968 each treatment has been divided into four main plots, testing four rates of fertilizer N: 0, 48, 96 and $144 \text{ kg N ha}^{-1} \text{ y}^{-1}$ (N_0 , N_1 , N_2 and N_3 respectively, Figure 1). These application rates span the range generally given to spring barley in England and Wales (The British Survey of Fertilizer Practice, 1995). Full details are given in successive Guides to the Rothamsted Classical Experiments (Rothamsted Experimental Station, 1970, 1977, 1991), by Warren and Johnston (1967) and by Jenkinson and Johnston, 1977.

Since 1968, the FYM and PK has been applied to the stubble shortly before ploughing in the autumn. N is applied in the spring shortly after sowing. Table 2 gives details of the field operations over the period reported in this paper. A liming scheme was started in spring 1955; ground chalk is now applied to maintain soil pH at ca.7.0.

Terminology

The original long-term fertilizer and manure treatments (PK, FYM, FYM-residue and Nil) are subsequently referred to as 'treatments'. The four rates of fertilizer N (N_0 , N_1 , N_2 and N_3) on each of the treatments are subsequently referred to as 'main plots'. The microplots receiving ^{15}N -labelled fertilizer are subsequently referred to as 'microplots'.

Application of ^{15}N -labelled fertilizer

^{15}N -labelled fertilizer (as $^{15}\text{NH}_4$ $^{15}\text{NO}_3$) was applied in spring 1986 and 1987 (Table 2) to three replicate microplots on the N_1 , N_2 and N_3 main plots of the PK and FYM treatments, and the N_3 main plots of the Nil and FYM-residue treatments. The amount of labelled fertilizer N applied was within 5% of the nominal rate of fertilizer N for the main experiment (i.e. 48, 96 and 144 kg N ha^{-1}). A trace amount (2.3 kg N ha^{-1}) of very highly labelled fertilizer N was also applied to the N_0 main plots of the PK and FYM treatments, subsequently referred to as the N_0^* microplots. The aim of these N_0^* treatments was to investigate N dynamics on the plots not receiving fertilizer N. Applications of such a small amount of N should have a negligible effect on the size of the soil inorganic N pool - with larger applications there is always a risk that the behaviour of N in the enlarged pool will differ from that in the smaller, unfertilized pool.

Table 1. Effect of long-term treatments on some soil properties in the Hoosfield Spring Barley Experiment

Treatment ^a code	pH	Olsen P ^b (mg kg ⁻¹)	Exchangeable ^c K(mg kg ⁻¹)	Organic C ^d (%)	Total soil ^e N content (%)		
	in H ₂ O				0–23 cm	23–50 cm	50–70 cm
PK	7.2	141	329	0.88	0.100	0.083	0.077
FYM	7.3	137	827	3.26	0.298	0.130	0.083
Nil	7.5	9	79	0.97	0.102	0.084	0.078
FYM-residue	7.3	13	104	1.33	0.133		

^a Figure 1 gives treatment details.

^b P soluble in 0.5 M NaHCO₃, measured in 1982.

^c Extracted in ammonium acetate, measured in 1982.

^d By dichromate oxidation, measured in 1982.

^e Mean of samples taken in 1986 and 1987 from all microplots receiving ¹⁵N in those years.

Table 2. Details of field operations

Operation	Harvest year	
	1986	1987
Glyphosate applied	-	6 Nov 1986
P, K, Mg applied ^a	18–20 Nov 1985	28 Nov 1986
FYM applied	20 Nov 1985	2 Dec 1986
Ploughed (to 23 cm)	21 Nov 1985	2 Dec 1986
Seedbed prepared:		
barley (c.v.Triumph) sown (160 kg ha ⁻¹)	17 Mar 1986	16 Mar 1987
Initial soil and crop samples taken	7 May 1986	23 Apr 1987
N applied (unlabelled areas)	12 May 1986	24 Apr 1987
N applied (¹⁵ N microplots)	12 May 1986	27 Apr 1987
Weedkillers and fungicides applied	16 May 1986	5 and 29 May 1987
Hand-harvested (¹⁵ N microplots)	28 Aug 1986	17 and 18 Aug 1987
Combine harvested (unlabelled areas)	29 Aug 1986	21 Aug 1987
Soils sampled	29 Aug–2 Sept 1986	18–24 Aug 1987

^a See legend to Figure 1 for details.

Figure 1 shows the position of the labelled areas on each main plot. This area was covered when the unlabelled fertilizer N was broadcast over the remainder of the plot, the covers were then removed and the ¹⁵N-labelled fertilizer applied. To avoid edge effects, each microplot was surrounded by a 0.5 m discard which received ¹⁵N-labelled fertilizer at the same rate as the microplot itself (Figure 1). In the second year, the ¹⁵N was applied to a different area within the main plot. In years when the microplots did not receive ¹⁵N-labelled fertilizer, they received unlabelled N at the customary rate for the main plot.

The ¹⁵N-labelled fertilizer was applied in solution, using a spreader designed to give even and accurate application (Woodcock et al., 1982). Each plot was then watered with 2 L of distilled water to wash the labelled solution off the plants and onto the soil.

Powlson et al. (1986b) demonstrated the effectiveness of this procedure. Recoveries of fertilizer N are all calculated from the actual amounts of ¹⁵N-labelled fertilizer applied to the microplots (Table 4), *not* the nominal additions to the main plots.

The ¹⁵N enrichments of the fertilizer applied in the spring were 5.194 and 4.897 atom % excess in 1986 and 1987 respectively for the N₁, N₂ and N₃ microplots, and 98.634 atom % excess for the N₀* microplot. Atom % excess is defined as (measured atom % ¹⁵N - 0.3663).

Crop and soil sampling at the time of the spring ¹⁵N application

Soil and crop samples were taken in the spring, shortly before the ¹⁵N was applied (Table 2) from outside the area which was later to receive the ¹⁵N. These samples

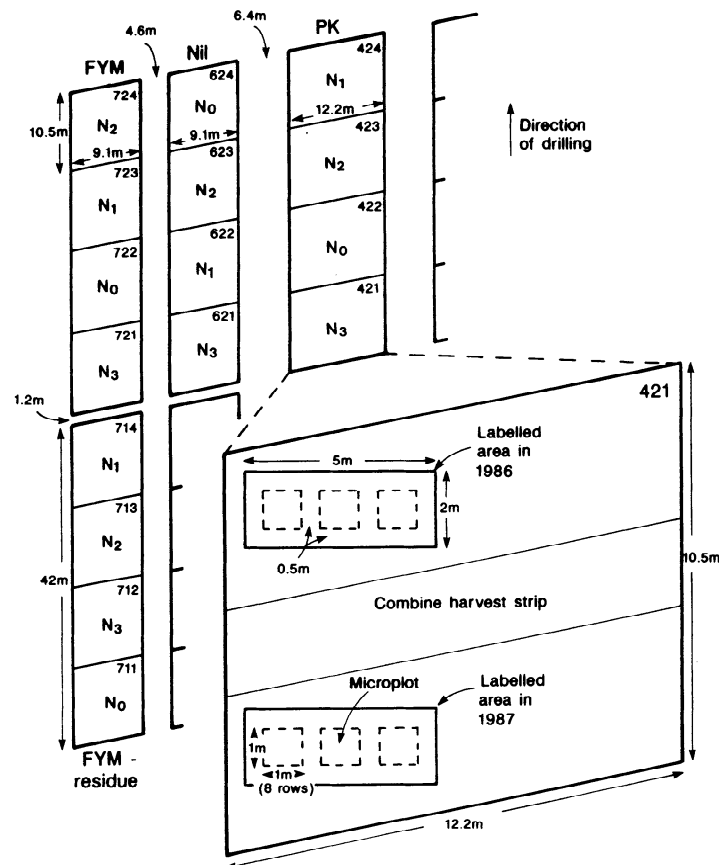


Figure 1. Plan of part of the Hoosfield Spring Barley Experiment showing dimensions and arrangement of main plots within each treatment strip. Enlarged view shows the position of the ^{15}N -labelled areas and microplots within one of the main plots.

Nil: no fertilizer or manure since 1852, but small amounts of ash applied 1852–1932.

PK: currently $35 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ as single superphosphate, $90 \text{ kg K ha}^{-1} \text{ yr}^{-1}$ as potassium sulphate, 35 kg Mg ha^{-1} as kieserite every third year. $48 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ as ammonium sulphate 1852–1967.

FYM: $35 \text{ t ha}^{-1} \text{ yr}^{-1}$ since 1852 containing, on average, 235 kg N ha^{-1} , 44 kg P ha^{-1} , 330 kg K ha^{-1} .

FYM-residue: $35 \text{ t ha}^{-1} \text{ yr}^{-1}$ 1852–1871; nothing since then.

N_0 , N_1 , N_2 , N_3 : 0, 48, 96, $144 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ as calcium ammonium nitrate since 1968. N rates rotate annually, $\text{N}_2 \rightarrow \text{N}_1 \rightarrow \text{N}_0 \rightarrow \text{N}_3$ (rates shown are those for 1987).

were used to measure the amount of N in the crop and the background ^{15}N enrichment of crop and soil at the time of ^{15}N application: soil inorganic N was measured at the same time. Duplicate samples were taken from each of the long-term treatments. Plants were pulled by hand from four 0.3 m rows, washed, then dried at 80°C . Soil samples (0–23 cm and 23–50 cm) were taken with a semi-cylindrical auger (2.5 cm diameter), each sample consisting of 6 or 8 cores.

Crop and soil sampling at harvest

Plants were cut by hand, approximately 5 cm above ground level, from each of the ^{15}N microplots. Samples

of stubble (including the crown, just below the soil surface, but no roots) were taken from two 1 m rows from each microplot. Loose soil on stubble samples was returned to the microplots, the remainder washed off. Some weeds were present on most plots and were cut at ground level from the whole microplot.

Yields and crop samples (grain and straw) were also taken from the main plots with a small plot combine (harvest area 1.5×9 or 12 m).

Soil samples were taken from the microplots with a petrol-driven post-hole screw auger, as described by Powlson et al. (1986b). It should be noted that this method of sampling shreds the roots and mixes them intimately with the soil. Two holes (30 cm diam.) were

drilled in each microplot for the 0–23 cm soil layer; the soil was sieved (< 25.4 mm), weighed, bulked, a 2 kg subsample kept and the remainder returned to the microplot. Samples for the 23–50 and 50–70 cm depths were taken from two holes (12.5 cm diam.) on one microplot only. The two other replicate microplots were not sampled below 23 cm, as they were to be used to measure the uptake of residual ^{15}N in subsequent years, and it was thought that sampling below the plough layer might alter the soil drainage characteristics. Soil from the two holes was bulked, sieved (< 25.4 mm) weighed, a 0.7 kg subsample taken and the remainder returned to the holes in correct depth order.

Sample preparation

The grain, straw and chaff were separated by a stationary thresher. Subsamples (as described by Powlson et al., 1986b) were oven-dried (80 °C for 18 hr), then ground in a disk mill (Tema model T100), which was washed between samples to avoid cross contamination. The soil was sieved (< 6.25 mm 0–23 cm depth, < 12.5 mm 23–50 and 50–70 cm depths) and a 500 g subsample air-dried, then ground as for plant material.

Analytical methods

Total N was determined in the finely ground plant and soil samples by the Chromium III modification of the Kjeldahl method to include nitrate-N (Pruden et al., 1985a). $^{14}\text{N}/^{15}\text{N}$ ratios were measured with a VG Micromass model 602D mass spectrometer (see Pruden et al., 1985b for details). Nitrogen content and ^{15}N enrichment of the fertilizer solutions used in the field were measured by steam distilling diluted aliquots with MgO and Devarda's alloy and converting the resulting $\text{NH}_4\text{-N}$ to N_2 (Pruden et al., 1985b).

Soil inorganic N in the spring samples was determined in 62.5 g fresh sieved (< 6.25 mm) soil (approximately 50 g oven-dry soil), shaken for 1 hour with 200 mL 2 M KCl. $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ were measured colorimetrically in the filtered extracts (Whatman No. 1 filter papers) with a Technicon Auto Analyser (Litchfield, 1967). The combined results ('inorganic N') are presented, as the soils contained very little $\text{NH}_4\text{-N}$ (< 1 $\mu\text{g g}^{-1}$ soil).

Soil inorganic N in the harvest samples was determined in the finely ground air-dried subsamples, as the frozen undried samples had been inadvertently destroyed. Dried soil (50 g) was extracted as described

above. Total inorganic N and the $^{14}\text{N}/^{15}\text{N}$ ratios were determined with an automatic N analyser linked to a mass spectrometer (Robo-Prep Tracer Mass, ANCA-MS, Europa Scientific, Cheshire, UK).

Dry weights and N contents of grain, straw, chaff, stubble and weeds are expressed on an oven-dry (80 °C) basis, except for grain yields in Figure 2, which are expressed at 85% dry matter (DM). Analyses of soil were carried out on the air-dried material, but results are expressed on an oven-dry basis (105 °C), determined by oven drying a separate sub-sample.

The mass of sieved oven-dry soil in each soil layer was determined for each microplot from 1986–1989 inclusive. There were no significant differences between the soil weights of the PK, Nil and FYM-residue treatments, so mean values for these three treatments of 2.47 (SE \pm 0.019), 2.83 (\pm 0.058) and 2.55 (\pm 0.057) Mkg ha $^{-1}$ were used to calculate the amounts of labelled and unlabelled N in the 0–23, 23–50 and 50–70 cm layers, respectively. Soil from the FYM treatment was less dense and here mean weights of 2.29 (\pm 0.025), 2.75 (\pm 0.047) and 2.39 (\pm 0.052) Mkg ha $^{-1}$ were used for the 0–23, 23–50 and 50–70 cm layers, respectively.

Statistical analysis

All statistical analyses were performed using the GENSTAT 5 statistical package (Payne et al., 1993). The errors presented are the standard errors of the differences of the means; the residual degrees of freedom are also given as appropriate. Errors are based on the replicate microplot samples, as there is no true replication in the long-term treatments.

Results and discussion

Crop and soil N at the time of fertilizer application in the spring

Crop and soil samples were taken six weeks after sowing, just before the ^{15}N was applied (Table 2). In both years, barley on the FYM treatment contained nearly twice as much N as that growing on the other treatments, with a 30% greater dry weight (Table 3). There were no significant differences in crop dry weight or N content between the PK, Nil and FYM-residue treatments or between the two years at this time.

In 1986 the FYM treatment contained twice as much inorganic N in the soil (0–50 cm) as the other

treatments, with an extra 24 kg N ha^{-1} in the 23–50 cm layer (Table 3). In 1987 the difference was even greater. Again, there were no differences between the PK, Nil and FYM-residue treatments. There was 20–50% more inorganic N in the soil (0–50 cm) in 1987 than 1986 at the time of ^{15}N application.

Grain yield

There was generally good agreement between grain yields in the ^{15}N microplots and the combine harvested areas of the main plots (Figure 2). All microplot yields were within 20% of the main plot yields, and most were within 10%.

Grain yields were about average for cv. Triumph spring barley on Hoosfield, a mean maximum of 6.7 t ha^{-1} (FYM N_2 in 1986 and 1987), compared to the mean maximum yield of 6.6 t ha^{-1} over the period when cv. Triumph was grown (FYM N_2 , 1984–90, Rothamsted Experimental Station, 1991). In the absence of fertilizer N, yields from the FYM treatment were more than twice those of the PK treatment, 5.7 and 2.5 t ha^{-1} respectively (1986 and 1987 mean). The Nil and FYM-residue treatments receiving N_0 yielded 12–29% less than the PK N_0^* microplot.

The crops showed the typical response to fertilizer N by spring barley on Hoosfield (Figure 2). There was little or no increase in grain yield on the PK treatment above the N_2 rate. Yields on the FYM treatment showed little increase above the N_1 rate, and a reduction at the N_3 rate due to lodging. In 1987, the FYM and PK treatments gave similar yields, provided enough fertilizer N was applied to the latter (Figure 2). In 1986 yields on the FYM treatment, given fertilizer N, were greater than the following year; on the PK treatment yields were less and could not match those on the FYM treatment, no matter how much fertilizer N was applied. The FYM plots contain much more organic matter than the PK plots (Table 1), so that soil physical conditions, such as bulk density, are more favourable for crop growth. This suggests that soil physical conditions were more critical for crop growth in 1986, when the rainfall in May and June was only 78 mm, than in 1987 (May and June rainfall 154 mm).

There was a much smaller response to fertilizer N on the Nil and FYM-residue treatments than on the PK treatment, with a maximum yield of 4.4 t ha^{-1} (Nil N_3 , 1987) compared to 5.9 t ha^{-1} from the PK N_3 plot in 1987. Without adequate P and K, the barley was unable to make full use of the fertilizer N applied. There were

no consistent differences between the yields on the Nil and the FYM-residue N_3 plots.

Weed

Weeds were present on most plots, but the amounts of N taken up (labelled and unlabelled) were generally small ($< 5 \text{ kg N ha}^{-1}$), with the exception of the FYM-residue plots ($8.5\text{--}13.6 \text{ kg N ha}^{-1}$) and the FYM N_0^* in 1987, which took up 11 kg N ha^{-1} (Table 5). In all cases, the weed contained $< 5\%$ of the labelled N applied.

Uptake of total N

Uptake of total (i.e. labelled plus unlabelled) N increased with fertilizer application over the whole range of applications in the PK treatments, but there is clear evidence of saturation in the FYM treatments (Table 4). Similar patterns were obtained over the two years of our experiments with labelled N and on the main Hoosfield experiment over the eight years 1984–1991. Saturation effects - Bloom et al.'s (1988) 'break point' - are well known in over-fertilized cereal crops.

Labelled fertilizer N in crop and weed at harvest

In the PK and FYM treatments, labelled N uptake by the crop (plus weed, where present) increased linearly with the rate of fertilizer N applied, the relationship (taking both treatments, all four N rates and both years together) being given by:

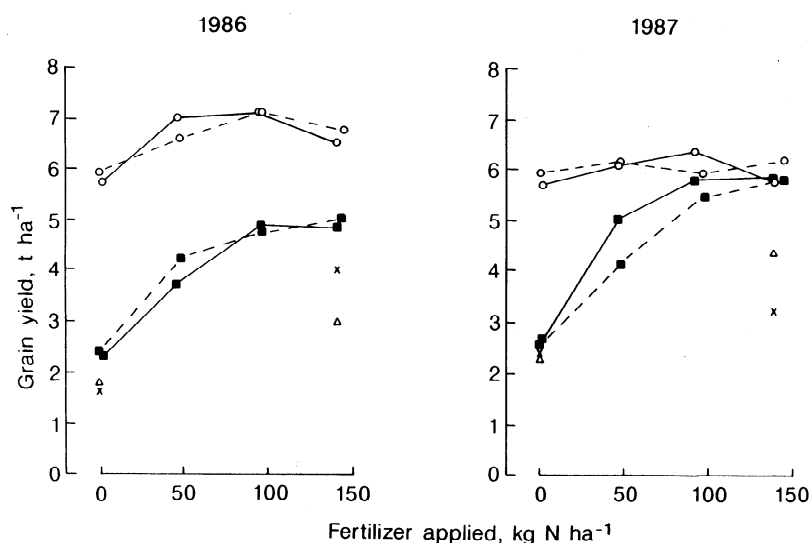
$$\begin{aligned} & \text{(labelled N recovered at harvest} & (1) \\ & \text{in crop plus weeds, kg ha}^{-1}) \\ & = (-0.94 \pm 0.643) + (0.52 \pm 0.007) \\ & \text{(labelled N added, kg ha}^{-1}), \text{ with } r = 0.999. \end{aligned}$$

The mean percentage recovery of labelled fertilizer N in crop and weed at harvest was 49.8% (range 46.3–52.7%) in the PK and FYM N_1 , N_2 and N_3 plots (Table 4; see Table 5 for a breakdown of uptake between crop components). There were no consistent differences in percentage recovery between the two years or between these two long-term treatments. However, percentage recoveries tended to increase as nitrogen applications increased, particularly with the PK treatment.

These results are very similar to other ^{15}N studies with spring barley. Dowdell et al. (1984) reported

Table 3. Crop dry matter, N content of crop and inorganic N content of soil at time of spring ^{15}N application

Year	Fertilizer ^a treatment code	Crop DM (t ha ⁻¹) (OD basis)	Crop N content (kg ha ⁻¹)	Inorganic N in soil (kg ha ⁻¹)		
				0–23 cm	23–50 cm	0–50 cm
1986	PK	0.16	3.9	15	18	33
	FYM	0.21	7.4	25	42	67
	Nil	0.13	3.6	9	16	25
	FYM-residue	0.13	3.5	12	11	23
	SED ^b	0.062	1.33	2.7	1.8	4.1
1987	PK	0.13	3.5	16	24	40
	FYM	0.17	6.2	44	53	97
	Nil	0.11	3.3	15	20	35
	FYM-residue	0.12	3.4	17	18	35
	SED	0.008	0.33	5.5	3.1	8.5

^a See legend to Figure 1 for details.^b Standard errors of differences of means, 4 DF.Figure 2. Grain yields (t ha⁻¹, at 85% DM) in 1986 and 1987 from the hand-harvested ^{15}N -labelled microplots (■—■ PK, ○—○ FYM, △, Nil, × FYM-residue), and from the surrounding combine harvested main plots (■--■ PK main plot, ○--○ FYM main plot).

recoveries of 45.6–53.5% in the above-ground crop in a lysimeter study with a shallow silt loam overlying Chalk. Thomsen (1993), also with a lysimeter study, found recoveries of 45.9–52.2% in grain and straw after applying 104 kg N ha⁻¹ to three sandy soils in Denmark. The uptake of *unlabelled* N from two of these sites was twice that from the third site (mean of 119 compared to 66 kg N ha⁻¹), yet, as with our results from the FYM plots, the recovery of fertilizer N was very similar (49 compared to 47%). Nielsen et al. (1988) reported a somewhat wider range (43–67%) of recoveries at harvest for spring barley grown over

three years on a sandy loam in Denmark, given 30–150 kg N ha⁻¹. Lyngstad (1990) reported recoveries of 66–70% in a three year lysimeter experiment with spring barley: % recoveries were similar across a range (80–240 kg N ha⁻¹) of fertilizer applications. McTaggart and Smith (1995) found mean recoveries of just under 50% for $^{15}\text{NH}_4$ $^{15}\text{NO}_3$ applications to spring barley in the field: again % recovery was independent of rate of addition over the range 60–150 kg N ha⁻¹. Kjellerup and Kofoed (1983) measured a mean recovery of 55%, with the percentage increasing slightly as the fertilizer application increased.

Table 4. Fate of ^{15}N -labelled fertilizer N applied in the spring to spring-sown barley in the Hoosfield Continuous Barley Experiment in 1986 and 1987

Year and fertilizer treatment ^a		Labelled N applied ^b (kg N ha ⁻¹)	N in above ground crop and weed (kg N ha ⁻¹)		Labelled N in soil (kg N ha ⁻¹)				Percentage recovery of fertilizer N ^c					
			Labelled	Unlabelled	0–23cm	23–50 cm	50–70 cm	Total 0–70 cm	In grain	In above ground crop and weed	In soil 0–70 cm	In crop, weed and soil 0–70 cm	Lost	
1986														
PK	N ₀ *	2.32	0.88	38.1	1.16	N.D	N.D	1.16 ^d	28.3	37.5	49.7 ^d	86.9 ^d	13.1	
	N ₁	46.7	21.6	45.7	15.5	0.8	0.8	17.1	33.7	46.3	36.5	82.8	17.2	
	N ₂	94.6	48.5	51.4	25.5	2.6	1.3	29.4	38.5	51.2	31.1	82.3	17.7	
	N ₃	140.9	74.3	42.2	35.7	3.7	2.3	41.7	39.5	52.7	29.5	82.2	17.8	
FYM	N ₀ *	2.32	0.87	108.1	0.88	N.D	N.D	0.88 ^d	28.0	37.0	37.9 ^d	74.9 ^d	25.1	
	N ₁	46.7	24.6	117.7	11.6	1.3	0.9	13.8	42.2	52.7	29.6	82.3	17.7	
	N ₂	94.6	47.0	113.4	26.7	3.3	2.5	32.5	38.7	49.4	34.3	83.7	16.3	
	N ₃	140.9	70.2	90.7	33.3	6.1	3.6	43.0	36.5	49.8	30.5	80.3	19.7	
Nil	N ₀	0	0	36.4	-	-	-	-	-	-	-	-	-	
	N ₃	140.9	50.4	26.7	45.5	N.D	N.D	51.6 ^e	26.1	35.8	36.6 ^e	72.4 ^e	27.6	
FYM-residue	N ₀	0	0	41.2	-	-	-	-	-	-	-	-	-	
	N ₃	140.9	62.1	40.0	43.3	N.D	N.D	49.9 ^e	33.3	44.1	35.1 ^e	79.2 ^e	20.8	
SED ^f			2.66	3.82	1.29	N.D	N.D	N.D	2.42	2.76	2.93 ^g	3.31 ^g	3.30 ^g	
SED ^f N ₀ * only			0.053	1.73	0.14	N.D	N.D	N.D	2.33	2.24	6.02 ^g	4.01 ^g	4.01 ^g	
1987														
PK	N ₀ *	2.31	0.80	38.7	1.14	0.04	0	1.18	25.2	35.0	51.3	86.3	13.7	
	N ₁	46.0	22.0	49.8	15.1	0.3	0	15.4	35.1	47.9	34.5	82.4	17.6	
	N ₂	91.4	43.5	50.9	28.7	1.4	0	30.1	35.0	47.6	33.0	80.6	19.4	
	N ₃	138.7	72.9	46.8	36.2	3.1	0.6	39.9	38.0	52.6	28.8	81.4	18.6	
FYM	N ₀ *	2.31	0.97	121.8	0.71	0	0	0.71	26.9	42.1	30.5	72.6	27.4	
	N ₁	46.0	21.6	135.5	10.7	0.8	0	11.5	28.7	47.0	24.9	71.9	28.1	
	N ₂	91.4	45.4	131.2	27.0	2.5	0	29.5	29.3	49.8	32.3	82.1	17.9	
	N ₃	138.7	69.7	104.2	36.3	3.5	1.7	41.5	30.9	50.3	30.0	80.3	19.7	
Nil	N ₀	0	0	35.0	-	-	-	-	-	-	-	-	-	
	N ₃	138.7	66.2	36.8	42.4	4.4	0.6	47.4	33.8	47.7	34.2	81.9	18.1	
FYM-residue	N ₀	0	0	43.2	-	-	-	-	-	-	-	-	-	
	N ₃	138.7	52.4	37.3	44.2	6.0	0.9	51.1	25.5	37.8	36.9	74.7	25.3	
SED ^f			2.29	4.58	2.05	N.D	N.D	N.D	2.72	3.22	2.70 ^g	3.78 ^g	3.78 ^g	
SED ^f N ₀ * only			0.046	3.82	0.103	N.D	N.D	N.D	1.67	2.03	4.46 ^g	3.75 ^g	3.75 ^g	

ND – not determined

^a See legend to Figure 1 for details of long-term fertilizer treatments.

^b Actual amount of labelled N applied.

^c The % recovery given in the table may not exactly agree with the values obtained by calculating from the data given in the table because of rounding up.

^d 23–70 cm assumed to be 0.0 kg N ha⁻¹, as in 1987.

^e 23–70 cm assumed to be 6.1 kg N ha⁻¹ (mean of PK and FYM N₃ treatments in 1986, and all N₃ treatments in 1987).

^f Standard errors of difference of mean 24 DF, except labelled N and % recovery, which is 20 DF, and N₀ * only, which is 4 DF.

^g SE for 0–23 cm depth only, as no replicates for 23–50 and 50–70 cm depths.

Labelled fertilizer N in soil at harvest

The quantity of labelled-N remaining in the soil (0–70 cm) at harvest was also linearly related to the amount of labelled fertilizer added. For the PK and FYM treatments (taking both treatments, all four N rates and both years together) this relationship was given by:

$$\begin{aligned}
 &(\text{labelled N remaining in the soil, kg ha}^{-1}) \quad (2) \\
 &= (0.75 \pm 0.742) + (0.30 \pm 0.009) \\
 &(\text{labelled N added, kg ha}^{-1}), \text{ with } r = 0.994.
 \end{aligned}$$

The mean recovery of labelled N in the soil for the N₁, N₂ and N₃ microplots of the two treatments was 31% (range 24.9–36.5%), with an indication that % recovery was less at the higher N rates in the PK treatment (Table 4). Thus, the total recovery of fertilizer N in the crop, weed and soil at harvest in the PK and FYM N₁, N₂ and N₃ microplots was 80.3–84.0%, excluding 1987 FYM N₁ which had a total recovery of only 71.9%, due to a relatively low recovery of N in the soil (24.9%, 0–70 cm).

Table 5. Yields of crop components and weeds (all expressed on an oven-dry basis) and their labelled and unlabelled N contents, 1986 and 1987

Year and fertilizer treatment ^a	Grain				Straw				Chaff				Stubble				Weeds			
	Yield (t ha ⁻¹)	Labelled (kg N ha ⁻¹)	Unlabelled (kg N ha ⁻¹)	Yield (t ha ⁻¹)	Labelled (kg N ha ⁻¹)	Unlabelled (kg N ha ⁻¹)	Yield (t ha ⁻¹)	Labelled (kg N ha ⁻¹)	Unlabelled (kg N ha ⁻¹)	Yield (t ha ⁻¹)	Labelled (kg N ha ⁻¹)	Unlabelled (kg N ha ⁻¹)	Yield (t ha ⁻¹)	Labelled (kg N ha ⁻¹)	Unlabelled (kg N ha ⁻¹)	Yield (t ha ⁻¹)	Labelled (kg N ha ⁻¹)	Unlabelled (kg N ha ⁻¹)		
<i>1986</i>																				
PK	N ₀ [*]	1.99	0.66	27.2	0.93	0.09	0.34	0.04	1.7	0.38	0.06	2.3	0.19	0.02	3.0	0.19	0.02	3.0		
	N ₁	3.13	15.7	31.4	1.77	2.5	0.47	0.7	1.5	0.63	1.5	3.2	0.38	1.2	4.0	0.38	1.2	4.0		
	N ₂	4.12	36.4	38.2	2.04	5.2	0.79	2.0	2.1	1.16	4.9	5.4	0	-	-	0	-	-		
	N ₃	4.09	55.6	30.5	2.33	9.9	0.73	3.0	1.8	0.91	5.8	3.6	0	-	-	0	-	-		
FYM	N ₀ [*]	4.85	0.65	83.9	2.06	0.09	0.64	0.03	2.9	0.89	0.09	7.1	0.22	0.01	4.9	0.22	0.01	4.9		
	N ₁	5.96	19.7	95.2	2.88	2.9	0.99	0.9	4.1	0.70	1.1	5.3	0	-	-	0	-	-		
	N ₂	6.04	36.6	88.1	2.83	6.2	0.83	1.5	3.5	0.65	2.4	5.8	0.06	0.2	0.6	0.06	0.2	0.6		
	N ₃	5.49	51.5	65.9	3.02	10.5	1.07	3.6	4.7	0.79	4.6	5.8	0	-	-	0	-	-		
Nil	N ₀	1.54	0	23.7	1.00	0	0.26	0	1.6	0.30	0	1.9	0.22	0	4.3	0.22	0	4.3		
	N ₃	2.55	36.7	17.7	1.24	5.9	0.52	2.5	1.4	0.51	3.1	1.8	0.28	2.21	2.5	0.28	2.21	2.5		
FYM- residue	N ₀	1.40	0	21.6	0.66	0	0.24	0	1.3	0.22	0	1.4	1.01	0	13.6	1.01	0	13.6		
	N ₃	3.42	46.9	25.8	1.42	6.6	0.65	2.7	1.7	0.58	3.7	2.4	0.51	2.28	6.2	0.51	2.28	6.2		
SED ^b	N ₀ [*]	0.235	2.53	2.98	0.222	0.85	0.082	0.40	0.37	0.099	0.37	0.66	0.209	1.41	3.03	0.209	1.41	3.03		
SED ^b N ₀ [*] only		0.135	0.054	1.51	0.116	0.012	0.020	0.003	0.11	0.076	0.007	0.56	0.143	0.009	2.73	0.143	0.009	2.73		
<i>1987</i>																				
PK	N ₀ [*]	2.27	0.58	26.6	1.18	0.08	0.41	0.05	2.5	0.67	0.07	3.7	0.16	0.02	2.1	0.16	0.02	2.1		
	N ₁	4.24	16.1	35.1	2.49	2.5	0.68	1.2	2.8	1.00	1.7	4.0	0.22	0.6	2.1	0.22	0.6	2.1		
	N ₂	4.90	31.9	36.5	2.96	5.5	0.87	3.0	3.5	1.11	2.9	3.9	0.05	0.3	0.4	0.05	0.3	0.4		
	N ₃	4.98	52.6	32.9	3.45	11.0	0.96	5.7	3.6	0.87	3.6	2.8	0	-	-	0	-	-		
FYM	N ₀ [*]	4.82	0.62	80.0	2.77	0.11	0.88	0.05	6.6	1.78	0.09	10.1	0.64	0.10	10.9	0.64	0.10	10.9		
	N ₁	5.15	13.2	83.0	4.17	4.3	0.98	1.4	8.6	1.32	1.9	12.5	0.22	0.8	3.6	0.22	0.8	3.6		
	N ₂	5.39	26.7	76.9	4.50	9.8	1.07	3.2	8.9	1.19	3.7	11.4	0.34	2.1	3.8	0.34	2.1	3.8		
	N ₃	4.91	42.8	62.3	4.30	16.6	1.08	5.9	8.4	0.86	4.5	7.1	0	-	-	0	-	-		
Nil	N ₀	1.95	0	24.9	0.91	0	0.35	0	2.3	0.60	0	3.4	0	-	-	0	-	-		
	N ₃	3.71	46.8	25.3	1.98	8.0	0.89	5.9	3.3	1.05	5.5	3.4	0	-	-	0	-	-		
FYM- residue	N ₀	2.00	0	25.8	0.84	0	0.35	0	2.1	0.62	0	3.4	0.54	0	8.5	0.54	0	8.5		
	N ₃	2.73	35.3	19.7	1.56	6.6	0.68	3.8	2.6	0.65	3.7	2.4	0.64	3.1	7.1	0.64	3.1	7.1		
SED ^b	N ₀ [*]	0.339	1.94	3.21	0.209	0.37	0.051	0.18	0.35	0.202	0.64	1.43	0.120	0.31	1.19	0.120	0.31	1.19		
	SED ^b N ₀ [*] only	0.158	0.038	3.01	0.171	0.011	0.019	0.005	0.27	0.297	0.007	1.52	0.136	0.021	1.72	0.136	0.021	1.72		

^a See legend to Figure and Table 4 for details of the fertilizer treatments.

^b Standard errors of the difference of means, 24 DF, except labelled N content which is 20 DF, weed, which varies from 12 to 16 DF, and N₀^{*} only, which is 4 DF.

Most (77–98%) of the labelled N recovered in the soil was in the 0–23 cm layer (Table 4). Twice as much labelled N was recovered in the 23–70 cm layer in 1986 as in 1987 (mean of PK and FYM N₁, N₂ and N₃ microplots), as would be expected from a wetter soil which received a little more rain in the three weeks after fertilizer application (53 mm in 1986, 46 mm in 1987). There was nearly twice as much labelled N in the 23–70 cm layer of the FYM N₁, N₂ and N₃ microplots than in the corresponding PK microplots.

Above-ground recoveries of fertilizer N applied in spring to *autumn*-sown cereals tend to be a little greater than those observed here for N applied to spring barley, with a little less N remaining in the soil. Thus, Powlson et al. (1992) reporting on nine experiments over four years in Eastern England with winter wheat given 48–234 kg N ha⁻¹ as ¹⁵NH₄ ¹⁵NO₃ found that recoveries of fertilizer N in the above-ground crop ranged from 46 to 87% (mean 68%), with an average of 18% remaining in the soil (0–70 cm). Macdonald et al. (1997) reported a recovery of 55% by winter wheat grown in 1987 on a field 500 m from Hoosfield, with 20% remaining in the soil (0–70 cm). The reason for this difference between spring-sown and autumn-sown crops is presumably that autumn-sown crops have already established an extensive root system by the time the fertilizer is applied. Spring-sown crops have not, so more of the fertilizer N has to be assigned to root production.

Losses of fertilizer N between spring and harvest

In the PK and FYM treatments, loss of labelled N (or strictly, labelled N not accounted for in crop, weed and soil) increased linearly with application of fertilizer N, the relationship for both years and all four N rates being given by:

$$\begin{aligned} & \text{(labelled N not recovered in crop, soil} & (3) \\ & \text{and weed at harvest, kg N ha}^{-1}) \\ & = (0.14 \pm 0.643) + (0.19 \pm 0.007) \\ & \text{(labelled N added, kg N ha}^{-1}), \text{ with } r = 0.989. \end{aligned}$$

In absolute terms, losses were greatest from the N₃ microplots, the largest being 39 kg N ha⁻¹ (27.6% of the N applied) from the Nil N₃ microplot in 1986 (Table 4). In this experiment, the fertilizer N was applied six weeks after the crop was sown. In practice, the N is often applied directly to the seedbed, before any root system has developed, and so losses may be greater. Powlson et al. (1992) found a strong linear relationship

between ¹⁵N not accounted for at harvest and rainfall in the three weeks following fertilizer application, given by the regression:

$$L_{70} = 5.0 + 0.264R_3, \text{ with } r = 0.85 \quad (4)$$

where L₇₀ = the percentage of labelled fertilizer N not recovered at harvest in the crop or soil to 70 cm, and R₃ = cumulative rainfall (in mm) in the three weeks following ¹⁵N fertilizer application in spring. Here, the measured loss of fertilizer N in 1986 was 17.7% (mean of PK and FYM N₁, N₂ and N₃ microplots), compared to a predicted loss by the regression of 18.9%. The corresponding mean measured loss in 1987 was 20.2%, compared to 17.2% by the regression. This suggests that the general relationship derived from winter wheat between loss of fertilizer N and rainfall in the three weeks after fertilizer application may also be applicable to spring barley.

There are clear indications (see section below on recovery of N from trace applications) that denitrification cannot be a major loss process of ¹⁵N in these experiments. This is confirmed by estimates of denitrification made by Webster (1996) on the Hoosfield experiment, based on field measurements of N₂O evolution, using *in situ* flux chambers that contained acetylene to block the conversion of N₂O to N₂. In 1990, 3 kg N ha⁻¹ or less was denitrified in the two months following fertilizer application in each of the PK and FYM N₀ and N₃ main plots. In 1989, denitrification losses were greater: 2 kg N ha⁻¹ from PK N₀, 9 from PK N₃, 11 from FYM N₀ and 15 from FYM N₃, all over the 10 weeks following addition of fertilizer N. The calculated potential soil moisture deficit for Rothamsted soil when the fertilizer was applied was 29.1 mm in 1986, 36.1 in 1987, 12.0 mm in 1989 and 36.7 in 1990. Rainfall in the three weeks following application was 52.7 mm in 1986, 46.2 mm in 1987, 67.6 mm in 1989 and 18.5 mm in 1990. Losses in our experiment, done in 1986 and 1987, would therefore be more like those measured by Webster in 1990 than those in the wet spring of 1989, when the soil was wetter when the fertilizer was applied and more rain fell in the following three weeks.

Leaching cannot be a major loss process in these experiments either. The potential soil moisture deficits over the period between application of labelled fertilizer and harvest never fell below 11 mm in 1986 (reaching 110 mm by harvest) and 18 mm in 1987 (reaching 59 mm by harvest), so saturated leaching of the profile could not have occurred in either year. Even

if by-pass flow occurred, so that leaching to below rooting depth could occur in an unsaturated soil, it is most unlikely that more than a very few kg of fertilizer N could have been leached to below rooting depth. Calculations made for Rothamsted soils by the WATER leaching model (Nabeel Mirza, personal communication), showed that less than 1% of the labelled fertilizer N would have been leached to below 50 cm between application and harvest in both 1986 and 1987, even if it is assumed that the soil was saturated at application time, that all the fertilizer is added as nitrate and that plant uptake is zero. The soil was not saturated when the fertilizer was added, the fertilizer was NH_4NO_3 , and plant uptake was not zero, all factors that would further decrease losses by leaching.

Labelled nitrogen may have been lost by volatilization of NH_3 . Such losses are small for NH_4NO_3 applied in solution to Rothamsted soils in spring (Powelson et al., 1986b; Yamulki et al., 1996), but it is possible that larger quantities of NH_3 were released from the crop during senescence (Schjørring et al., 1989; Sharpe et al., 1988). Schjørring et al. (1993) measured losses of 0.5–1.5 kg $\text{NH}_3\text{-N ha}^{-1}$ from the canopy of a well-fertilized spring barley crop over the growing period, similar in magnitude to the losses of NH_3 measured by Yamulki et al. (1996) from winter wheat at Rothamsted.

Losses of 10–20% of applied fertilizer N from the soil/crop system are by no means uncommon in lysimeters and field experiments with spring barley (Bertelsen and Jensen, 1992; Bole and Gould, 1986; Kjellerup and Kofoed, 1983; Knight and Sparrow, 1993; Lyngstad, 1990), although occasionally much larger (Kowalenko and Cameron, 1978; Smith and Gyles, 1989) or smaller (Malhi et al., 1996) losses have been observed. Careful experiments on plants grown in closed growth chambers (Craswell and Martin, 1975) have shown that recovery of both $^{15}\text{NO}_3^-$ and $^{15}\text{N}_4^+$ can be virtually complete under favourable conditions. However, there is little doubt that crops maturing in the field *can* lose canopy N to the atmosphere under certain (as yet ill-defined) circumstances. Whether NH_3 volatilization is sufficient to explain these losses is an open question.

Unless we have seriously underestimated some or all of the various loss processes considered above, it is difficult to see how a loss of 18.5% of labelled N could have occurred across the whole range of fertilizer applications in these experiments, suggesting that other loss mechanisms, some perhaps unknown, must also have contributed.

Recovery of N in crop, weed and soil from trace applications of labelled N

Although data from the microplots given 2.3 kg highly-labelled N ha^{-1} have been included in Equations 1, 2 and 3, some features of the N_0^* microplots require special comment. On both the PK and FYM treatments, the percentage recovery of fertilizer N by *crop and weed* was consistently lower in the N_0^* microplots than in the N_1 , N_2 and N_3 microplots (Table 4). Conversely, on the PK treatment, the percentage recovery of labelled N in the *soil* was consistently greater in the N_0^* microplots: it was also greater in the FYM treatment, although less markedly so. The net result is that the overall recovery of ^{15}N by crop, weed and soil in the PK N_0^* microplot (86.6%; mean of both years) was 4.6% *greater* than that for the PK N_1 , N_2 and N_3 microplots (82.0%; mean of both years). On the FYM treatment it was the other way round: the corresponding recovery in the FYM N_0^* microplot was 6.4% lower than in the FYM N_1 , N_2 and N_3 microplots. The reasons for these differences are instructive. Cereals allocate a greater proportion of their N to roots when N is in short supply (Clarkson, 1986; Wellbank, 1974). Of all the microplots receiving labelled N, the PK N_0^* microplot contains least plant-available N (i.e. inorganic N in soil and fertilizer), so it is not surprising that this microplot had the largest percentage of its labelled N in the soil (Table 4).

Denitrification is almost certainly the reason why the loss of labelled N from the crop/soil system was greater in the FYM N_0^* microplot than the PK N_0^* microplot. In 1986 the FYM N_0^* microplot lost 0.28 kg N more labelled N than the PK N_0^* microplot (12% of that added); in 1987, 0.32 kg (14% of that added). Denitrification is set by O_2 demand by the soil population and, inversely, by the rate at which this demand is met by diffusion from the atmosphere: it is independent of the amount of NO_3^- present, unless this becomes limiting. At equivalent water potentials, the O_2 demand of the FYM plot would be markedly greater than that of the PK plot, which contains only a third of the organic N and C (Table 1).

The small difference, of some 0.3 kg N ha^{-1} , between the loss of labelled N from the FYM N_0^* and the PK N_0^* microplots can only be measured because the trace addition was very highly enriched with ^{15}N (Table 4). Such a small difference would be undetectable over the N_1 , N_2 and N_3 range, with much larger SEDs (Table 4). However, if the *extra* N lost by denitrification from the FYM N_0^* microplot over the PK N_0^* microplot (12% in 1986; 14% in 1987) was

also lost from the FYM N₁, N₂ and N₃ microplots, then losses from these microplots should also be significantly greater than from the corresponding PK N₁, N₂ and N₃ microplots. Table 4 shows that this is not so, powerful evidence that losses of fertilizer N by denitrification do not amount to more than a few kg ha⁻¹, irrespective of rates of fertilizer application.

Recovery of fertilizer N by spring barley when P and K are limiting

In both years, the percentages of N in grain and straw were consistently greater on the Nil and FYM-residue treatments than in the PK treatment, whether or not N was applied (derived from data in Table 5). However, because yields were less when P and K were in short supply, the uptake of N by crop and weed was similar in the Nil N₀, FYM-residue N₀ and PK N₀* treatments and markedly less in P and K deficient crops given N₃ (Tables 4 and 5).

More labelled N remained in the soil when P and K were limiting than when not, with an indication in 1987 (Table 4) that at least some of this additional N was in the 23–50 cm layer. Overall losses of N from the crop/soil system were, with one exception (Nil N₃ in 1987), greater when P and K were limiting. In general, the greater the yield depression (compared to yields on the PK treatment) the greater the overall loss of fertilizer N from the system.

Unlabelled N in crop and weed at harvest

The uptake of unlabelled N from the FYM treatment was more than twice that from the other treatments, a mean of 115 kg N ha⁻¹ (both years and all four N rates), compared to 41 kg N ha⁻¹ (Table 4). Almost 15% more unlabelled N was taken up from the FYM treatment in 1987 than in 1986. This additional uptake was in the straw, chaff and stubble, not in the grain (Table 5). The uptake of unlabelled N from the FYM N₃ microplot was 20% less than from the other FYM microplots in both years: there was evidence for a similar trend in the PK N₃ microplots in 1986 and 1987. In both years, less unlabelled N was taken up from the PK and FYM N₀* microplots than from the corresponding PK and FYM N₁ microplots.

The mean uptake of unlabelled N in crop and weed for the Nil treatment (both years and both N rates) was 33.7 kg N ha⁻¹, somewhat less than the corresponding mean for the FYM-residue treatment (40.4 kg ha⁻¹),

presumably because of a little N coming from the FYM applied long ago.

Inorganic N in the soil at harvest

Unfortunately, because of the failure of a deep-freezer, the inorganic N content of the soils had to be measured in finely ground dried and stored soil, giving results that are high compared to measurements on fresh soil (Table 6). From 1.5 to 4.1% of the labelled fertilizer N originally applied was present in inorganic form in the 0–23 cm layer of soil at harvest (Table 6). Had we been able to analyse properly stored soil, even less labelled inorganic N would have been found.

These estimates of the amount of labelled inorganic fertilizer N present in the soil at harvest are similar to those obtained for winter wheat in south-east England. Macdonald et al. (1989) found that < 5 kg N ha⁻¹ fertilizer N remained in the soil at harvest in inorganic form after 11 winter wheat crops given between 47 and 234 kg N ha⁻¹. Thus, in this experiment with spring-sown barley, there is no evidence that more inorganic fertilizer N is at risk to loss over the following winter than with comparable autumn-sown cereals.

Fertilizer use efficiency

Figure 3 shows the fertilizer use efficiency (i.e. % recovery of added fertilizer N), as calculated from the recovery of ¹⁵N labelled fertilizer by the above-ground crop and weed. It also shows fertilizer use efficiencies as calculated by two different versions of the non-isotopic 'difference' methods, one based on 'step-by-step' differences in uptake by successive increments of fertilizer and the other by regression of total N uptake on N applications over the whole range of applications.

It is immediately obvious that the three methods give radically different results for fertilizer use efficiencies - as usual with such experiments (Harmsen and Moraghan, 1988). Taking the PK treatments first, the regression version of the difference method gives a fertilizer use efficiency of 57–58% across all N rates in both years. The ¹⁵N method gives recoveries markedly below this, particularly at the lower end of the N scale. These results are consistent with the explanation put forward by Hart et al. (1986), who showed that a pool substitution process, driven by microbial immobilization of inorganic N, could quantitatively account for the difference between these two ways of measuring fertilizer use efficiency. The step-by-step difference

Table 6. Inorganic N in dried, finely ground and stored soil (0–23 cm) at harvest, 1986 and 1987

Year and fertilizer treatment ^a			Inorganic N in soil (kg N ha ⁻¹)		Labelled inorganic N as % of fertilizer N applied
			Total	Labelled	
<i>1986</i>					
PK	N ₀ *	2.32	30	ND	-
	N ₁	46.7	33	1.0	2.2
	N ₂	94.6	35 ^c	1.7	1.8
	N ₃	140.9	39	2.2	1.5
FYM	N ₀ *	2.32	57	ND	-
	N ₁	46.7	53	0.7	1.5
	N ₂	94.6	73 ^d	2.9	3.0
	N ₃	140.9	66	3.6	2.5
SED ^b			3.1	0.24	0.24
<i>1987</i>					
PK	N ₀ *	2.31	45	ND	-
	N ₁	46.0	31	1.1	2.3
	N ₂	91.4	37	2.0	2.2
	N ₃	138.7	29	2.6	1.8
FYM	N ₀ *	2.31	81	ND	-
	N ₁	46.0	88	1.9	4.1
	N ₂	91.4	84	3.3	3.6
	N ₃	138.7	72	5.4	3.9
SED ^b			7.8	0.55	0.55

^a See Figure 1 for details.^b Standard errors of the difference of means, 16 DF.^c Measured in fresh soil 22 kg inorganic N ha⁻¹ (Powelson et al., 1989).^d Measured in fresh soil 37 kg inorganic N ha⁻¹ (Powelson et al., 1989).

method shows an irregular decline in N efficiency with increasing applications of fertilizer N.

Now consider the FYM treatments. Here the regression version of the difference method cannot be used, because of marked curvilinearity in the relationship between N uptake and fertilizer application. Fertilizer use efficiencies, as calculated by the 'step-by step' difference method, are extraordinarily high at the low end of the fertilizer scale, 75% in 1986 and 79% in 1987 (Figure 3). We do not know why. Lyngstad (1990) made a similar observation in lysimeter experiments with spring barley. At the high end of the scale, fertilizer use efficiency falls essentially to zero. Yet the ¹⁵N measurements show that spring-applied fertilizer is taken up with about 50% efficiency across the whole N₁, N₂ and N₃ scale. The *only* explanation possible

is that spring-applied fertilizer blocks the uptake of soil N, once the capacity of the crop to take up N is exceeded. Table 6 indicates that there were no consistent differences in the nitrate contents of the top 23 cm of soil across the whole span of fertilizer applications in the FYM treatment, so that this unused unlabelled inorganic N in the N₃ microplot was not in the top 23 cm: it must have been deeper in the profile. Fertilizer N uptake is usually virtually complete by anthesis (Schjørring et al., 1989; Thomsen, 1993) with uptake of soil N continuing till senescence. Nitrate uptake is a balance between active ATP-driven input processes and passive (and presumably concentration driven) efflux (Clarkson, 1986). It may be that the roots in the 23–70 cm layer just do not take up unwanted nitrate - or a passive efflux process may be at work in the

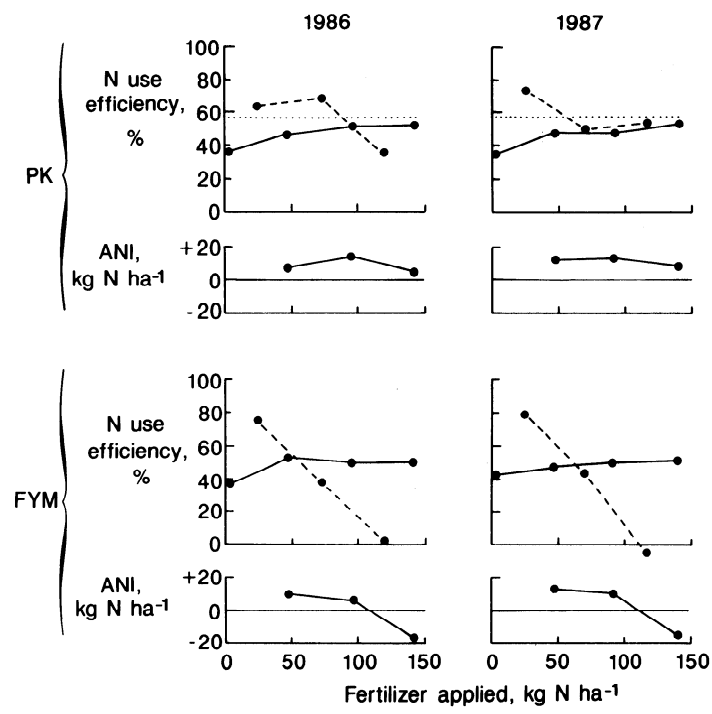


Figure 3. Fertilizer use efficiency (i.e. % recovery of added fertilizer N by above-ground crop and weed), as calculated from the recovery of ^{15}N -labelled N (●—●) and by the non-isotopic difference method. The difference method calculations were made in two ways: from the difference in N uptake from successive applications of fertilizer (●---●) and by linear regression of N uptake on N applications over the whole range of applications (...). Note that the regression method could only be used with confidence for the PK treatments ($r = 0.992$ in 1986; 0.996 in 1987); the corresponding regressions for the FYM treatment (0.918 and 0.893 respectively) were too poor (because of curvilinearity) for this approach to be useful. The corresponding Added Nitrogen Interactions (ANIs) are shown in the lower part of each diagram.

deeper soil layers. It is also possible that less soil N is taken up from the deeper layers because fewer roots are present: large applications of N fertilizer may well discourage deep rooting, particularly on fertile soils such as that from the FYM treatments. Such differences in rooting depth should be reflected in the water content of the deeper layers when sampled at harvest. In 1987 the water content of the 50–70 cm layers of the FYM treatment increased consistently in the order N_1 , N_2 and N_3 . However in 1986 no such consistent differences were observed.

From the agronomic point of view, the observation that the % recovery of labelled N in grain, straw, stubble and weed (or, for that matter, in grain alone: Table 4) is relatively similar across the whole N scale in both high and low organic matter soils is of little interest. Of more interest is the grain response to fertilizer N. This falls sharply from 30 kg grain per kg fertilizer N (mean for the PK and FYM treatments in Table 4, calculated from the difference in yield between

N_0 and N_1 applications) to a negative value (i.e. a yield depression) for the N_3 – N_2 difference.

Added nitrogen interactions

Figure 3 shows the Added Nitrogen Interactions (ANIs; Jenkinson et al., 1985) for the PK and FYM treatments. ANI is here defined as the uptake of unlabelled N by a crop given labelled fertilizer N, less the uptake of N by the crop given no fertilizer N. Because there were no true zero N microplots on the PK and FYM treatments, unfertilized uptakes were taken as those by crops given 2.3 kg labelled N ha⁻¹. Although not strictly correct, this quantity of fertilizer N is too small to affect the calculated ANIs appreciably, whether they be real or apparent. There is a small positive ANI (3–12 kg N ha⁻¹) across the whole range of fertilizer applications in the PK treatments and at the lower end of the N scale in the FYM treatments. This is almost certainly caused by immobilization of inorganic N by the soil microbial biomass during the growth of the

barley, a process which gives rise to a positive *apparent* ANI by pool substitution (Hart et al., 1986: for similar results with barley grown in Alaska see Knight and Sparrow, 1993). However, in the FYM treatment, the ANI became negative at the top end of the N scale. Here the explanation is that given in the previous section: fertilizer N blocked the uptake of inorganic N from the deeper layers of the soil, once the capacity of the crop to take up N had been exceeded - an example of a negative real ANI.

Conclusions

The salient (and unexpected) feature of this work is that the percentage recovery of fertilizer N was similar in soils that contained very different amounts of organic and inorganic N. The treatment that receives FYM (0.30% organic N in soil) contained more than twice as much unlabelled inorganic N as the PK treatment (0.10% organic N in soil) when fertilizer N was applied, yet recovery of that fertilizer N in the above-ground crop at harvest was about 51% in both treatments, across all N rates. Yet total uptake of N fell off at the higher N rates, particularly in the FYM treatment. Fertilizer N blocks uptake of (unlabelled) inorganic N, particularly from the deeper soil layers, once the capacity of the crop to take up N is exceeded. Just under 20% of the fertilizer N was lost from the soil/crop system, irrespective of rate of addition. Denitrification and leaching were almost certainly insufficient to account for all this loss and other mechanisms, some perhaps as yet unknown, must also have contributed.

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